Event-driven MAC Protocol For Dual-Radio Cooperation

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***Abstract*—One of the sources of the energy waste in wireless sensor networks is idle listening, the time in which a node monitors the free channel. In applications where the events occur sporadically, energy consumption due to idle listening can be further reduced by dual-radio cooperation. In dual-radio cooperation, nodes in the network have two stacks. One stack makes use of a low-power wake-up radio for event-driven communication over the main radio. The other stack may employ any sensor networking medium access control protocol only over the main radio. One of the two stacks can be dynamically operational depending on the rate of the events or the packet arrival rate. When the event rate becomes small, the event-driven stack takes over the operation. If the event rate increases, it could be more efficient to operate the legacy single radio stack. In this paper, we investigate the performance of the dual-radio cooperation in wireless sensor networks. A medium access control protocol is proposed for the dual-radio cooperation to maximize the energy efficiency of the wireless network. We define the critical event rate as the event rate threshold above which the single-radio stack performs better than the dual-radio stack. We analyzed and validated the critical event rate by simulations. We show that 70-97% energy conservation is possible by employing the dual-radio cooperation.**

I. Introduction

Nodes in a wireless sensor network (WSN) may be battery-enabled devices and may not be permanently connected to a power source. Replenishing batteries in many applications may not be a feasible approach (e.g., harsh environments). Therefore, minimizing the energy consumption of WSNs is of significant importance. The factors that impact the energy consumption of sensors can be categorized by the OSI layers [1]. Factors related to data link layer, which is the focus of our work, include overhearing, idle listening, and retransmissions due to collisions. Since a large proportion of the total energy consumption of wireless sensor nodes is due to idle listening, minimizing the idle listening period conserves energy.

For successful data delivery, the destination should listen to the medium to be able to receive data when the sender transmits data packets which is referred to as rendezvous. The most energy-efficient rendezvous scheme is utilizing wake-up radios. Pure synchronous rendezvous requires time synchronization and consumes considerable energy because of idle listening or overhearing. In pseudo-asynchronous rendezvous, source nodes wake up and emit a preamble signal. The preamble time is long enough to coincide with the schedule of the destination node. Upon sensing the preamble, the destination recognizes the intended packet transmission. Nodes follow a duty cycle and consume considerable amount of energy with preamble signaling although time synchronization is not required [3].

In pure asynchronous rendezvous, sensors reside in deep sleep and can be woken up by their neighbors on demand with very low-power event-driven radio receivers. The event-driven operation of a network is viable with the use of a low-power wake-up radio, instead of sleep scheduling of the nodes. This reduces superfluous energy consumption caused by rendezvousing. Through event-driven communications, idle listening, overhearing and retransmission due to collisions can be minimized, a significant reduction in energy consumption and higher energy efficiency can be obtained. In an event-driven stack, the control channel is implemented over a low-power (wake-up) radio. The wake-up radio does not need a complex MAC or sophisticated front end [2]. It just monitors the channel and switches the main radio to active mode for data reception or transmission when receives a wake-up request from the other nodes. When a node has a packet to be sent, it transmits a wake-up request over its wake-up channel and then transmits the data packet over the main channel.

Depending on the rate of the events, utilization of the event-driven stack may become useless. If the events occur frequently, some sets of sensors have to sleep and wake up frequently. For such scenarios switching to periodic sleep scheduling may be wiser. For example, daytime operation of a museum surveillance network can be based on periodic sleep scheduling, whereas the night time operation can follow the event-driven scheme. Rigorous analysis of when to switch from event-driven to sleep scheduling is required when such a bi-modal operation is probable. For applications such as perimeter surveillance, the energy conservation gain of an event-driven architecture is enormous. However, when the rate of the events increases, the gain decreases, in which case employing a sleep scheduled MAC protocol may be more feasible. Assuming that events follow a stochastic process, if the sensors are equipped with wake-up radio and are also capable of running a sleep-scheduled MAC, then determining the feasible operational regions for both technologies becomes

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an optimization problem. When to use the event-driven or sleep-scheduled MAC is the key question to be answered. To answer this question, we define the critical event rate concept in this paper.

In this work, we concentrate on the identity-based active wake-up radio receivers. For the classification of the wake up receivers, readers may refer to [1]. We investigate the performance of the dual-radio node and describe the critical event rate concept. A MAC protocol for the dual-radio node is proposed and compared with the Zigbee stack which works based on carrier sense multiple access with collision avoidance (CSMA/CA) scheme. The wireless node energy consumption is calculated with an analytical model and validated by simulations. Furthermore, the critical event rate is computed and an event-driven MAC protocol is designed for dual-radio cooperation based on the achieved results.

The rest of this paper is organized as follows: In Section II, the dual-radio cooperation model and the critical event rate concept are presented. In Section III, the analytical models are validated by simulations. Lastly, we conclude the paper in Section IV.

II. Dual-radio Cooperation

In the dual stack cooperation model, we assume that each node in the network mutually employs two different types of medium access scheme. These are:

1) **Legacy medium access** (i.e, Zigbee in this work): when the event rate becomes large, useless state transitions between the on and off states will occur and employing a legacy medium access will perform better compared to the event-driven medium access.
2) **Event-driven medium access**: for low event-rates, this stack is employed. The details are presented in Section II-A.

The node adapts to the event rate by shifting its mode of operation from one scheme to the other. For low-event rate scenarios, event-driven medium access is employed. If the event-rate increases exceeding a threshold, the legacy medium access scheme is taken into force. We refer to this threshold as the critical event rate.

The critical event rate threshold may not be reached by all the nodes in the network at the same time. The main radio of a node which expects to receive a wake-up request packet is in sleep mode cannot handle the data packet that is sent by a neighbor which has already switched to legacy mode of operation. A single bit in the wake-up request message may represent the mode of operation for the next transmission.

In this work, the MAC protocol of the dual-radio node works based on the CSMA/CA process like the Zigbee protocol. The difference is that the dual-radio node invokes the CSMA/CA to send the wake-up request packet over the wake-up radio channel while the Zigbee MAC invokes CSMA/CA to send data packets over the main radio channel. The Zigbee protocols can be beacon- or non-beacon-enabled. In non-beacon-enabled networks, which is the focus of our work, an unslotted CSMA/CA channel access mechanism is used.

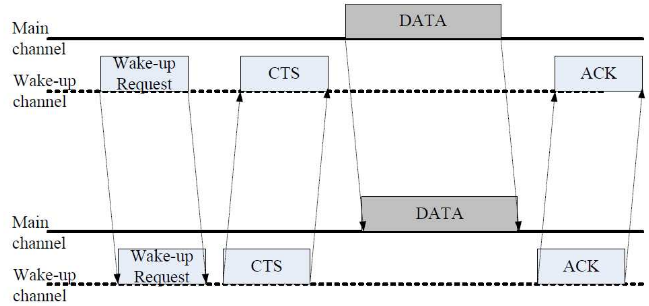

Fig. 1. The event driven medium access protocol messaging sequence. Wake-up radio channel is employed as the control channel and data packets are conveyed over the main channel. The sender initiates the communication with a wake-up request packet and the destination responds with the clear-to-send (CTS) packet.

We present the details of the event-driven medium access in the sequel.

A. Event-driven Medium Access

The event-driven medium access protocol is shown in Fig. 1. We assume that wake-up request contains the address of the destination. All the neighbors of the sender do not switch their main radio on, and the energy waste due to overhearing and extra switching is eliminated. When a node has data to send, it first sends a wake-up packet containing the address of the destination over the wake-up radio channel. Upon receiving this wake-up request (which is similar to the request-to-send (RTS) control packet), the destination node sends a clear-to-send (CTS) control packet over the wake-up radio channel, and turns its main radio on. After receiving data, the receiver sends an acknowledgement (ACK) packet back to sender. This wake-up request and CTS handshake avoids the hidden terminal problem (for data packets).

The receiver of the wake-up request packet may be busy or the wake-up packet may be lost over the channel. In this case, there would be energy waste due to turning on the main radio uselessly. On the other hand, if the node waits for the CTS packet to turn its main radio on, there will be increased delay and increased probability of collision of data packets since another node may start a transmission session during this period. Considering all these, the successful notification of the CSMA/CA process is considered to be the best time of triggering the main radio on.

B. Analytical Model

In this section, the methods to calculate the energy consumption of legacy single radio and event-driven dual-radio wireless nodes are given. In [5], it is proposed that the total energy consumption of a node can be expressed as

$$E(t) = N_T(t)E_T + N_R(t)E_R + T_S(t)P_S + T_I(t)P_I, \quad (1)$$

where $N_T(t)$ and $N_R(t)$ are the number of times that a node transmits and receives a packet over a period of length t unit time. $T_S(t)$ and $T_I(t)$ are the total time that a node spends in sleep and idle states within the period of length t. P_S and P_I

are the power consumption during sleep and idle modes. E_T and E_R are the energy required to transmit and receive one packet. $N_T(t)$ and $N_R(t)$ can be computed as

$$N_T(t) = \lambda_T t, \tag{2}$$

$$N_R(t) = \lambda_R t, \tag{3}$$

respectively where λ_T and λ_R are the rate of packet transmission and reception, and t is length of the period over which we compute the energy consumption.

Using (1), we can compute the energy consumption of a node for various MAC protocols. $N_T(t)$ and $N_R(t)$ depend on the event rate and the period for which we are computing the energy consumption. P_S and P_I depend on the radio model that is chosen. E_T, E_R, $T_S(t)$, and $T_I(t)$ are the parameters that depend on the MAC protocol. We use this basic formula to compute the energy consumption of a single-radio Zigbee node which works based on CSMA/CA, and an event-driven dual-radio node considering identity-based wake-up radio.

1) Zigbee Node Energy Consumption: The energy required to transmit a packet for Zigbee node is

$$E_T = P_T t_d + P_R(t_a + t_l + t_p), \tag{4}$$

where P_T and P_R are the power consumption of the radio in transmission and reception, respectively, and t_d, t_a and t_p are the durations of sending the data packet, the acknowledgement (ACK) and the processing delay, respectively. The time spent before sending a packet when a node has to report an event is denoted as t_l. This duration depends on the topology of the network and the number of the neighbors. If it is assumed that t_s is the time that each node senses the channel to see if the channel is busy or not, then

$$t_l = \sum_{i=0}^{Z-1} (1 - p_s)^i (p_s)(t_s + t_b(i)) \tag{5}$$

where p_s is the probability of successful transmission, and Z is the maximum number of back-offs that is allowed. $t_b(0)$ is zero and for other values of i we can write:

$$t_b(i) = N_B(i) \tag{6}$$

unit times where $N_B(i)$ is the number of back-off periods in the i^{th} attempt where $i = 1, \ldots, Z$. The method of computing the number of back-off periods is as follows: at each time a number is chosen randomly from the values between zero and $2^x - 1$, in which x is the back-off exponent. Each time when the channel is busy, the back-off exponent is incremented.

The energy consumed by the receiver to receive a packet and to acknowledge it becomes

$$E_R = P_T t_a + P_R(t_d + t_p) \tag{7}$$

In this model, we do not consider sleep scheduling. That is, we assume that the nodes are always on and the sleep time is zero, $T_S = 0$. The total time spent in idle state in a period of length t is

$$T_I = t - (N_T(t_d + t_a + t_l + t_p) + N_R(t_d + t_a + t_p)) \tag{8}$$

Inserting these parameters into (1), yields the Zigbee node energy consumption in a period of length t.

2) Dual-radio Node Energy Consumption: For the dual-radio node, we assume that the wake-up receiver is identity-based, and it uses internal power source for switching the main radio. The node invokes the CSMA/CA process to send a wake-up request over the wake-up radio channel, and transmits data over the main radio channel after receiving the clear-to-send (CTS) control packet over the wake-up radio channel. The required energy for transmission and reception of a packet for dual-radio node can be calculated as

$$E_T = P_T t_d + P_{TW} t_t + P_R(t_p + t_a) + P_{RW}(t_{CTS} + t_l + t_p) + E_{on} + E_{off}, \tag{9}$$

$$E_R = P_T t_a + P_{TW} t_{CTS} + P_R(t_p + t_d) + P_{RW}(t_t) + E_{on} + E_{off}, \tag{10}$$

where P_{TW} and P_{RW} are the wake-up radio's power consumption during transmission and reception, while P_T and P_R are the same parameters for the main radio (i.e., as defined after (4)). E_{on} and E_{off} are the energy consumption to switch the radio on and off, respectively. The sleep time and idle listening time are

$$T_S = t - (t_d + t_a + t_p + t_l)(N_T + N_R), \tag{11}$$

$$T_I = t - (N_R + N_T)t_t. \tag{12}$$

Note that the sleep time is the time that the main radio spends in sleep state since we assume that the wake-up radio is always active and monitors the channel. The idle time is the idle time of the wake-up radio, because the main radio is only active when it is involved in transmission or reception of the packets. With the assumption that the wake-up radio always consumes the same power no matter whether it is transmitting, receiving, or monitoring the channel, we have:

$$E_T = P_T t_d + P_R(t_p + t_a) + E_{on} + E_{off}, \tag{13}$$

$$E_R = P_T t_a + P_R(t_p + t_d) + E_{on} + E_{off}, \tag{14}$$

$$T_S = t - (t_d + t_a + t_p)(N_T + N_R), \tag{15}$$

$$T_I = t. \tag{16}$$

III. Results and Discussion

Dual-radio node model is implemented in OpNeT (OPtimized Network Evaluation Tool) which is a discrete event simulator designed for performance analysis of computer networks [6]. In this work, we concentrate on the energy consumption of the event-driven dual-node cooperation in comparison to the Zigbee protocol.

The simulation parameters are presented in Table I. The wake-up radio consumes a constant power level of 50 μW [4], and its data rate is 1 $kbps$. For the main radio model, we consider two different radio types. The first one is Chipcon

TABLE I
SIMULATION PARAMETERS AND THEIR VALUES.

Wake up radio (IMEC [4])	
Power consumption	50 μW
Data rate	1 $kbps$
Main radio (Chipcon cc1000 [7] and IMEC [9])	
Chipcon cc1000 Tx power	36 mW
Chipcon cc 1000 Rx and Idle power	24 mW
IMEC Tx, Rx and Idle power	200 μW
Power in sleep mode for all radios	3 μW
Data packet size	1 $kbit$
Control packet size	128 $bits$
No ack messages	

cc1000 [7]. The Chipcon cc1000 consumes 36 mW in transmission and 24 mW in reception and idle states. The second radio model is the IMEC's proposal [9] which consumes 200 μW in transmission, reception, and idle modes. We assume that the power consumption of the sleep mode for all radios is 3 μW. We take the size of the data packet as 1 $kbits$, and the size of control message packets as 128 $bits$. We do not consider the ACK messages in our simulations since they have ignorable effect on the results.

We consider the energy consumption of a simple end device which just sends packets, and does not work as a relay for other messages. The simulations are repeated 30 times and the 90% confidence intervals are shown in the figures. The packet inter-arrival times indicated in the figures, follow exponential distribution.

A. Energy Conservation

The energy consumption values of a Zigbee end device and a dual-radio node over a one-hour period resulted from simulation and analytical model are shown in Fig. 2. We assume the nodes are equipped with Chipcon cc1000 as the main radio. The results show that for all assumed event rates, the energy saved compared to single-radio model, is more than 97%. Therefore, if the main radio model has much higher power consumption in comparison to the wake-up radio, a very large amount of energy can be conserved by employing the event-driven medium access scheme.

If we employ a low-power chip as the main radio, the dual-radio cooperation still impacts the energy consumption results significantly. The results for the case in which we employ IMEC's low-power radio as the main radio is shown in Fig. 3. The power consumption is considered to be the same for different states (on/off/idle) for the IMEC's chip. Therefore, we expect the same energy consumption for various event rates for single-radio Zigbee node. Since IMEC's radio has low power consumption, we see that the energy consumption of the Zigbee node is close to the dual-radio node. For very high event rates, the event-driven medium access scheme performs worse than Zigbee. This is due to large number of transitions from on to off state and vice versa which results in extra energy consumption.

When the event rate is one event per second, the energy consumption of the single-radio Zigbee node is less than the

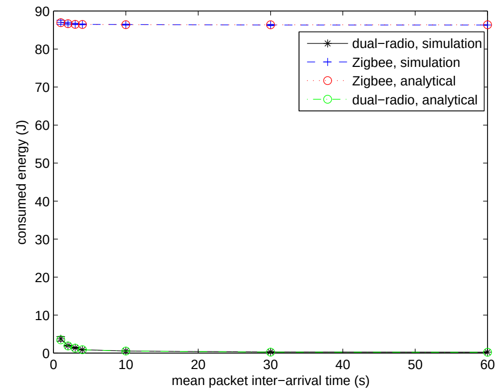

Fig. 2. Node energy consumption when the Chipcon cc1000 is employed as the main radio.

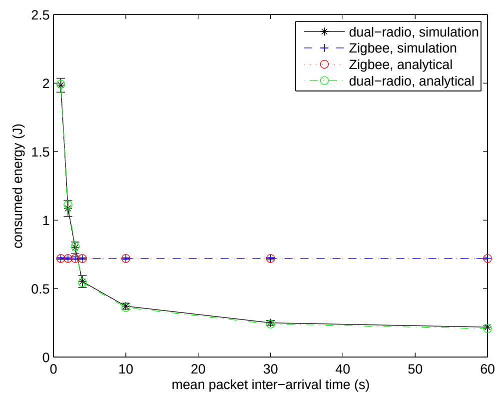

Fig. 3. Node energy consumption when the IMEC's low-power radio is employed as the main radio.

event-driven mode of operation. For low event rates the energy saving achieved by using the wake-up radio is around 72%.

B. Impact of Switching Energy Consumption

The energy required for switching the main radio to on or off states is assumed to be 250 μJ [10]. The effect of the switching energy (SE) on the performance of the dual-radio node and a reasonable range of switching energy from 77.5 μJ to 350 μJ are investigated using the IMEC's radio specification. For Chipcon cc1000, the event-driven mode of operation performs better than Zigbee for all reasonable values of switching energy. Note that some methods extract the energy from the radio signals for generating wake-up signals [10]. Therefore, they do not use the internal power supply for this operation. In our investigation, we assume that this energy is consumed from an internal power source.

Fig. 4 shows the effect of switching energy on the event-driven mode of operation. The critical event rate is defined as the rate above which the single-radio model consumes less energy than the dual-radio node. The intersection point of energy values of these two models represents the critical event rate.

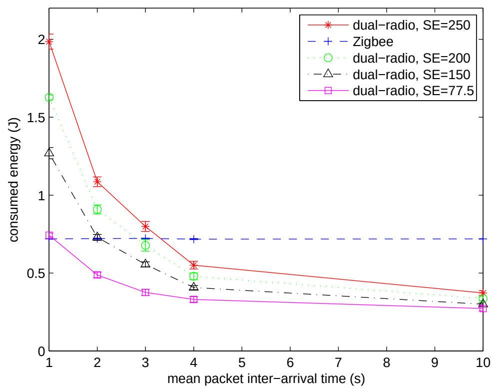

Fig. 4. Node energy consumption for different switching energy (SE) values using IMEC's radio model.

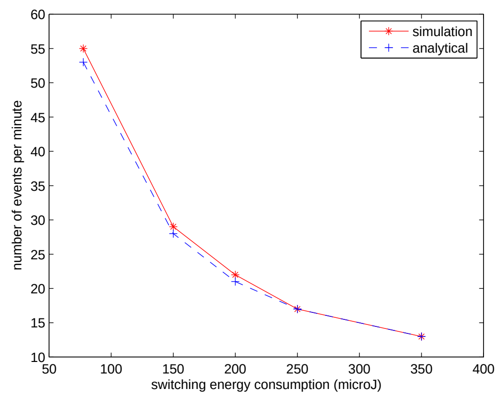

Fig. 5. Critical event rate (events per minute) for various value of the switching energy (SE).

Considering the results, the switching energy has a significant effect on critical event rate. We compute the critical event rate by detecting the intersection point of Zigbee energy consumption and dual-radio node for both simulation and analytical model and plot them in Fig. 5. The critical event rate decreases as the switching energy increases. As an example, the critical event rate for switching energy of 77.5 μJ is around 55 events/minute. In other words, if nearly one event per second happens, the energy consumption of the event-driven stack will become larger than the single-radio node.

If we assume a very small value for the switching energy, or consider the case in which the wake-up radio extracts the energy of the radio signals for triggering the main radio, we still can find a critical event rate for the dual-radio model. For very high event rates, dependent on the radios' data rate and packet sizes, it may be better to use the single-radio node model. In conclusion, defining the critical event rate for this case results in more efficient communication.

C. Dual-Radio Cooperation

The results show that for low event rates, the dual-radio node performs better than the single-radio model in terms of energy efficiency. For large event rates, the performance of the wake-up radio degrades. The idea of dual-radio cooperation is to use the wake-up radio for low event rates and switch to single-radio working principles when the event rate becomes larger than the critical event rate.

IV. Conclusion

Using a low-power wake-up radio is a reasonable choice to improve the energy efficiency of wireless sensor networks. It achieves a satisfactory communication delay while significantly decreasing the energy consumption. Reducing the energy dissipation in idle listening mode, decreasing overhearing and overhead, and reducing the number of retransmissions due to collisions are the results of using a low-power wake-up radio beside the node's main radio. In applications with a low event rate, event-driven medium access scheme consumes less energy than single-radio node. In applications with sporadic event rates, dependent on the radio models, the performance of the event-driven dual-radio node may degrade if the event rate is very large. By taking this phenomenon into consideration, we proposed the dual-radio cooperative stack to optimize the energy efficiency of the wireless node which employs the event-driven medium access in low event rates, and switching the mode of operation to legacy medium access schemes over a single radio when the event rate exceeds the critical event rate. As a future work, we will analyze scenarios with a larger number of nodes. Furthermore, determining a scalar value for the critical event rate may not a be a good option because of the fluctuations between the two modes of operation. Therefore, a hand-over region is to be defined. We will address this issue in a future work.

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